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RESEARCH MEMORANDUM

EXPERIMENTAL INVESTIGATION OF RIM CRACKING IN DISKS SUBJECTED TO HIGH TEMPERATURE GRADIENTS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

The results of an experimental investigation of rim cracking in a welded-blade composite gas-turbine wheel, in two carbon-steel disks, and in five tool-steel disks are presented.

In order to determine the effectiveness of holes in preventing crack propagation, 1/8-inch and 1/16-inch-diameter holes were drilled in the rim of the welded-blade composite gas-turbine wheel. Although causing the cracks to grow through the holes in the course of subjecting the wheel to thermal-stress cycles was impossible, the effectiveness of the holes in preventing crack growth was difficult to estimate accurately. The estimation was difficult because a considerable portion of the stress relief appeared to be occurring in a few long cracks, which existed before the holes were drilled in the rim. Crack growth occurred during the cooling part of the thermal-stress cycle.

The influence of hardness and various types of notch on rim cracking was investigated by subjecting 13.5-inch-diameter disks to thermal-stress cycles. It was impossible to cause cracks in the notched rims of carbon-steel disks with a maximum rim temperature of 1350° F because of the loss of hardness during the time that the rims were at the high temperature. In tapered tool-steel disks, cracks occurred more easily at 60°-V notches in the rim than at semicircular notches, as anticipated; 1/8-inch-diameter holes in the rim were more effective than 1/16-inch-diameter holes in stopping crack growth; the greater the hardness, the more easily the disks cracked.

INTRODUCTION

In the construction of gas-turbine wheels, welding has been used to attach blades to the rim of the wheel. Some of the advantages of welding over other methods of attachment are lower costs and more rapid fabrication; also on the basis of strength, a welded joint is a very efficient means of attaching the blades to the rim of the wheel. The experience of American and British manufacturers with the welded-blade construction has shown that cracks in the rim of the wheel between blades frequently occur during operation and these cracks limit the useful life of welded-blade turbine wheels.

The results of a preliminary investigation of the rim-cracking problem are reported in reference 1, in which the phenomenon of rim cracking in turbine wheels with welded blades is explained on the basis of the occurrence of plastic flow in the rim during starting of the turbine. It is stated in reference 1 that under starting conditions, the thermal compression stresses in the rim, resulting from the large temperature gradients, exceed the proportional elastic limit of the material and that when the wheel has cooled after operation, high residual tensile stresses, which may cause cracking, result. The beneficial effects, namely, reduction in crack propagation of axial holes at a small distance below the outer edge of the turbine disk or of radial slots in the rim between blades are discussed.

An experimental investigation of some of the factors influencing rim cracking in gas-turbine disks conducted at the NACA Lewis laboratory is reported herein. The effectiveness of holes in preventing crack propagation, the influence of hardness and various types of notch on rim cracking, and the point in the thermal-stress cycle at which crack growth occurs were investigated.

Turbine wheels with inserted blades were excluded from this investigation. In reference 1, it is stated that rim cracking is due to residual tension in the rim. Wheels with inserted blades have discontinuous rims and the part of the rim interrupted by the blade roots cannot sustain tangential tensile loading. The fact that rim cracking is rarely encountered in inserted blade wheels seems to confirm these statements. Many of the conditions associated with rim cracking in the continuous rim of a welded-blade turbine wheel can be simulated in a simple disk with a continuous rim and no blades. The investigation of some of the factors related to the rim-cracking problems was therefore conducted with simple disks. The investigations reported herein were conducted using: (a) welded-blade composite gas-turbine wheel; (b) carbon-steel disks; and (c) tool-steel disks.

The methods employed in obtaining and evaluating the results differed considerably for each of the three investigations. The report has been divided into three sections corresponding to the three investigations.

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WELDED-BLADE COMPOSITE GAS-TURBINE WHEEL

The most direct approach to the rim-cracking problem is to conduct experiments on the actual gas-turbine wheel. A high temperature gradient exists in the turbine wheel during the starting of a turbojet or turbine-propeller engine and plastic flow in compression may occur in the rim. If such plastic flow occurs, residual tensile stresses will be present in the rim after the turbine wheel has cooled. If rim cracking is the result of high residual tensile stresses, the propagation of cracks should take place during or after the cooling of the turbine wheel. The point in the thermal-stress cycle at which crack growth occurs was investigated in the welded-blade composite gas-turbine wheel. The drilling of holes at the ends of cracks has been quite widely used to prevent crack propagation. The value of drilled holes in preventing the growth of rim cracks in a gas-turbine wheel was also investigated.

Apparatus and Procedure

Turbine wheel and modifications. - The investigation was conducted on a composite-type gas-turbine wheel. The center was SAE 4340 steel. The $2\frac{1}{4}$-inch radial-thickness rim, which was welded to the center part of the wheel, was Timken 16-25-6. The blades were welded to the rim. The turbine wheel was one that had been operated in a turbine-propeller engine until cracks between the blades had progressed some distance into the rim. A photograph of part of the wheel at the time it was removed from service is presented in figure 1. The length of the cracks, dimension A (fig. 1), was measured from the edge of the bevel on the rim at the base of the blades. At the time the wheel was removed from service, the average length of all cracks was 0.22 inch.

The downstream side of the wheel, after holes were drilled in groups of four, with an average spacing of 12 blades between each group of holes is shown in figure 2. Table I gives the locations and the hole sizes. The holes were drilled on the radial line between the bases of two adjacent blades, as shown in figure 3. The distance, B (fig. 3), from the center of the holes to the bevel on the rim at the base of the blades varied from 3/16 inch to 5/16 inch as shown in table I. This distance was constant for each group of four holes. Holes were drilled at the base of approximately 25 percent of the blades. Six groups of four holes each or a total of 24 holes were 1/16 inch in diameter and six groups of four holes each were 1/8 inch in diameter.

Most of the cracks were somewhat shorter than the average of 0.22 inch, but a few cracks were much longer than 0.22 inch; consequently, when the holes were drilled, five of the long cracks extended beyond the holes. In the case of the other holes, the cracks did not appear to reach one-third of the holes and approximately two-thirds of the holes were drilled in such a manner that the cracks appeared to stop within the holes. The length of the cracks varied between the upstream and downstream sides of the wheel. The relative positions of the cracks before the runs with respect to the holes are shown by the first row of table II (number of thermal stress cycles, 0).

Measurements. - Crack gages were installed on the downstream side of the wheel, as shown in figure 2. The crack gages were similar to those described in reference 2. The crack gages consisted of a 0.001-inch-diameter Nichrome wire. About 1/2 inch of the wire was cemented to the wheel with ceramic cement. The wire was mounted perpendicular to the crack and at the end of the crack, or at a short distance beyond the end of the crack; when the crack propagated to the wire, the wire broke. A light bulb of the "grain of wheat" type was used in series with each gage to indicate the time at which it broke.

Crack lengths were measured at a magnification of approximately X4 with a cathetometer after every five or ten cycles of induction heating. Readings were accurate to about 0.4 millimeter. A small part of the crack-length data, reported for the early part of the program, was obtained by measurements from photographs in which the magnification was approximately X3.

Temperatures were measured with chromel-alumel thermocouples, which had been spot-welded to the downstream side of the wheel, as shown in figure 2. A multiple-point recording potentiometer was used to obtain the temperature distribution.

Setup and method of investigation. - The turbine wheel was subjected to cycles of thermal stress by induction heating. The equipment used is shown in figure 4. The power at a frequency of approximately 10,000 cycles per second was supplied by a 15-kilowatt induction-heating machine. The rim of the wheel at the base of the blades was heated by a pair of three-turn pancake-type inductor coils.

One coil was on the upstream side of the wheel and one coil, which can be seen in figure 4, was on the downstream side of the wheel. The turbine wheel was slowly rotated in the coils to obtain uniform heating along the circumference of the wheel; a temperature gradient existed in the radial direction of the wheel. The thermocouple lead wires and the crack-gage lead wires were allowed to twist slowly in one direction and then in the other direction. The maximum rotation of the wheel was approximately 2 revolutions in each direction.

The thermal-stress cycle consisted in heating the rim of the turbine wheel to 1150° F in approximately 25 to 30 minutes and then cooling the wheel by means of fans on both sides of the wheel. The temperature distribution during heating is shown in figure 5 and the temperature distribution during cooling is shown in figure 6. The rim of the wheel cooled very rapidly during the early part of the cooling cycle. After 1/2 hour of cooling, the maximum temperature in the wheel was approximately 220° F and the minimum temperature was approximately 170° F. The minimum cooling time was 1 hour, after which the temperature in the wheel was 100° to 150° F. During the process of heating, the edges of the holes and the cracks became red a few seconds before the main part of the rim, but this difference was not believed to be a serious effect.

Results and Discussion

<u>Cause of crack growth.</u> - The part of the thermal-stress cycle during which the cracks grew was determined by the crack gages. The indicator lights went out during the cooling part of the cycle indicating breaking of the crack-gage wire. Most of the gages failed in the period from 3 to 10 minutes after the induction-heating power was shut off. After a gage failed in the cooling part of the cycle, the gage would cause the indicator bulb to light again during the heating part of the cycle for a number of cycles following failure.

These results indicated that crack growth occurs during the cooling part of the cycle, because of the tangential tensile stresses. At no time during the cooling part of the cycle did the rim become appreciably cooler than the hub; consequently, any tensile stresses resulting from temperature gradients in the wheel during the cooling part of the cycle were negligible. The tensile stresses during cooling seem to be a result of plastic flow in compression that occurred during the heating part of the cycle. The fact that the broken crack-gage wires made contact again on reheating the wheel indicates that the cracks closed up because of compressive stresses during heating. These results therefore experimentally verify those of reference 1 in regard to the basic cause of the rim-cracking problem. 1148

Rate of crack growth. - The results of the measurements of crack length are presented in table III. The cracks shorter than 0.22 inch seem to have grown very little or none during the runs. One reason for the apparent negative growth of the short cracks was that when the length of a crack exceeded 0.22 inch, it was not reported in this group. The omission of the longer cracks may decrease the average crack length for the remaining cracks in the group. The inaccuracies in crack measurements may also have contributed to the apparent negative growth. In general, the long cracks grew much more rapidly than the short cracks. The manner in which the long cracks grew is shown in figure 7. The rate of growth for the long cracks increased as the length of the cracks increased. This increase seemed to indicate that as the testing progressed the portion of stress relief occurring in the long cracks became larger.

Effectiveness of holes in stopping crack growth. - The growth of the cracks at the locations where holes were drilled is shown in table II. Seven cracks progressed to the holes during the runs, but it was impossible to cause these cracks to progress beyond the holes. After 30 thermal-stress cycles, four cracks appear to have gone from the holes to the region beyond the holes. Figure 7 shows that for a given crack there is some variation between the upstream-side and downstream-side crack length. The crack length in the interior of the rim, between the two outside surfaces, may have been different from the crack length measured on either surface. Probably the four cracks that appear to have gone from the holes to the region beyond the holes actually extended beyond the holes in the interior of the rim at the time the holes were drilled. If any part of a crack actually extended beyond the hole at the time the hole was drilled, the hole naturally would not be effective in stopping crack growth.

The problem of cracks extending beyond the holes before these runs were started could have been avoided by drilling the holes at a greater distance from the edge of the rim; but this procedure was undesirable, because in a turbine wheel to be operated in an engine drilling the holes near the outer edge of the rim would be necessary to avoid excessively weakening the rim.

The rapid growth of the long cracks and the very small growth of the short cracks seem to indicate that a considerable portion of the relief of stresses resulting from cracking was taking place in the long cracks. These factors make the satisfactory evaluation of the crack-stopping effectiveness of the holes difficult. Observations of the individual cracks showed that the cracks not reaching the hole locations at the time the holes were drilled did not propagate beyond the holes. A more accurate determination of the effectiveness of holes in stopping crack propagation could be made if holes were drilled in the rim between every blade before cracks developed.

CARBON-STEEL DISKS

In thermal-stress runs of the type used in the preceeding investigation, the blades on a turbine wheel act similar to a series of notches along the rim. In order to investigate the influence of various types of notch on rim cracking, 13.5-inch-diameter disks were subjected to cycles of thermal stress.

Apparatus and Procedure

The disks were made of SAE 1045 steel and hardened to Rockwell C hardnesses of 28 to 30. The dimensions of the disks are shown in figure 8. A flat disk is shown in figure 8(a) and a tapered disk is shown in figure 8(b).

The equipment used to produce thermal-stress cycles and the equipment used to record temperatures are shown in figure 9. A 15-kilowatt induction-heating machine was used to heat the disks. A five-turn inductor coil heated the rim of the disk. After a few runs, the slip rings were not used. The disk was rotated 1 or 2 revolutions in one direction and then the direction of rotation was reversed. The thermocouple leads were allowed to twist as the disk rotated.

The rims of these disks were heated to a temperature of 1350° F in about 3 to 4 minutes and then cooled with jets of air on both sides of the disk. The temperature distributions during a thermal-stress cycle are shown in figure 10. The temperature of 1350° F represented the maximum rim temperature that was obtained in the cycle runs for each disk. The early thermal-stress cycles on each disk were carried out at lower maximum rim temperatures in order to establish the minimum temperature gradient required to cause rim cracking. Figure 11 shows the temperature distribution during the cooling part of a thermal-stress cycle. The cooling part of the cycle required from 3 to 5 minutes and was rapid at the rim during the early part of cooling. After the disk reached a temperature of 100° to 125° F a new thermal-stress cycle was started.

Results and Discussion

It was impossible to produce cracking at the notches in the rim under the previously described conditions. The flat disk was subjected to approximately 200 thermal-stress cycles and the tapered disk was subjected to approximately 20 cycles in which the maximum rim temperature was 1350° F. The conditions of the disks after the runs are shown in figures 12 and 13. The dark areas at the bottoms of the notches were brought out by removing the scale with a piece of emery cloth, which was supported by a flat piece of steel. These areas were depressions somewhat below the surface of the disks. The center parts were the regions of greatest depression in the dark areas. The areas at the bottoms of the notches resembled plastic-flow figures or Lüders' lines.

Hardness surveys taken after the runs were completed showed that the hardness at the edge of the rim was approximately Rockwell C-10. On the tapered disk, which had been subjected to only 20 thermal-stress cycles at 1350° F, the reduction in hardness started approximately $1\frac{1}{2}$ inches from the edge of the disk. In the case of a flat disk, which had been subjected to approximately 200 cycles at 1350° F, the reduction in hardness started approximately 3 inches from the edge of the disk. After a few cycles of heating, the rims of the disks lost their hardness and plastic flow occurred at the bottom of the notches. A possible factor contributing to the absence of cracking was that the maximum temperature of 1350° F at the rim was high enough to allow a considerable amount of stress relief in carbon steel during the time at which the rim was at that temperature.

TOOL-STEEL DISKS

The work on tool steel was a continuation of the investigation of the influence of various types of notch on rim cracking, and in addition, the effectiveness of holes in preventing crack growth and the effect of hardness on rim cracking were investigated. Because it was impossible to produce cracks in carbon-steel disks on account of the loss of hardness during the heating cycle, disks made from a tool steel that would maintain its hardness at the temperatures reached at the rim were used.

Apparatus and Procedure

The disks used in these experiments were a molybdenum high-speed tool steel, which is sometimes referred to as "a red-hard tool steel." The nominal chemical composition on a percentage basis was:

C	W	Mo	Cr	V	Fe
0.8	1.5	8	4	1	Balance

Five 13.5-inch-diameter tapered disks were used. The disks, each of uniform hardness, had Rockwell C hardnesses of 11, 38, 46, 60, and 65. The dimensions of the disks are shown in figure 14. The experimental equipment was the same as that used for the carbon-steel disks. (See fig. 9.)

The experimental program consisted of the following procedures:

(a) Ten cycles with a maximum rim temperature of 800° F were run, except for the disk with a Rockwell C hardness of 65.

(b) The maximum rim temperature was increased in 25° F increments and 10 cycles were run at each increment.

Each thermal-stress cycle was similar to that described in the preceding section. The temperature distributions were similar to those shown in figures 10 and 11.

Results and Discussion

<u>Occurrence of cracks.</u> - With one exception, the first crack occurred between the 60°-V notch and the 1/16-inch-diameter hole. The relation between the holes and the notches is shown in figure 14. In most cases, within a few cycles after the first crack occurred and at the same temperature gradient, cracks occurred at the remaining V notches irrespective of the presence of holes. With two exceptions, no cracks occurred between the semicircular notches and the holes. In the case of the V notches without holes, the cracks generally grew about 1 inch during the cycle in which they occurred. This initial growth seemed to occur in a very short time or instantaneously. During the cycle at which the crack passed through the hole, the crack length increased about 1/4 inch. The crack lengths increased very slowly after the cycle during which they occurred. The preceding statements about rates of crack growth apply to all of the disks except the one with low hardness (Rockwell C-11). The cracks in the low-hardness disk progressed

only a very short distance during the cycle in which they occurred. The appearance of cracks in the hard disks is shown in figure 15. A typical crack in the disk with low hardness is shown in figure 16.

Three cracks developed at the same temperature in the Rockwell C-65 disk. This disk was the first tool-steel disk to be investigated and too high a temperature was chosen for the initial heating cycle. Some operating difficulties were also encountered in the first cycle and the rim temperature may have momentarily been slightly higher than that measured by the recorder.

Effectiveness of holes. - The temperatures at which first cases of the several cracking phenomena occurred in the various disks are shown in figure 17. One point on each of the three curves was obtained from each disk. The hardness of the disks is indicated by the abscissa. The increase in temperature, above that producing cracks, required to cause the crack to progress through a 1/16-inch hole indicates the effectiveness of such a hole in preventing crack growth. The same statement may be made for the 1/8-inch holes, which were more effective than the 1/16-inch-diameter holes in preventing crack growth.

The cracks that had occurred at the bottom of the notches without holes were about 1 inch long, however, and the probability that these cracks were contributing considerably to the relief of rim stresses should not be overlooked. The presence of the 1-inch cracks probably required somewhat higher temperatures to force the cracks through holes than would have been required in their absence. The drilled holes were rather effective in stopping crack growth, but propagation of the cracks beyond the holes by increasing the maximum temperatures at the rim was possible. The relative effectiveness of the holes was evaluated by increasing the maximum rim temperature until the cracks were forced through the holes; the progression of the cracks through the holes in these runs does not mean that the holes were of no value.

Influence of hardness and other factors on rim cracking. - The disks of materials with Rockwell C hardnesses of 38 and 46 had low cracking temperatures as shown in figure 17. For this range of hardness, according to references 3 and 4, tool steels of this type have low toughness and impact strength. The toughness and the impact strength are higher for disks that are harder or softer than those disks in the Rockwell C hardness range from 38 to 46. The loss of toughness or impact strength seems to have been the significant factor in causing the low cracking temperatures for disks with Rockwell C hardnesses of 38 and 46. In general, from figure 17, reducing the hardness of the disk evidently increases resistance to cracking.

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Hardness surveys of the tool-steel disks, after induction-heating runs, showed no change in hardness and no variation in hardness from the center to the rim.

The tool-steel disk with a hardness of Rockwell C-11 had about the same hardness as that measured in the rims of the carbon-steel disks after testing. Cracks were produced in tool-steel disks, whereas no cracks were produced in carbon-steel disks. Carbon steel of this hardness has high ductility. A reduction in area of 56 percent for SAE 1045 steel of this hardness is reported in reference 5. The reduction in area of tool steels of this type and hardness is stated to be around 20 percent in reference 6. The lower ductility of the tool steel was a factor of considerable importance in causing rim cracking. Tool steel requires higher temperatures for stress relief and for softening (references 4, 6, and 7), and this requirement may also account for part of the difference in rim cracking.

SUMMARY OF RESULTS

The following results were obtained from an experimental investigation of rim cracking in a welded-blade composite gas-turbine wheel, in carbon-steel disks, and in tool-steel disks:

Welded-Blade Composite Gas-Turbine Wheel

The composite gas-turbine wheel had a low-alloy SAE steel center, a heat-resisting alloy rim, and welded blades. The wheel had developed cracks in the rim during operation in an engine before 1/8-inch and 1/16-inch-diameter holes were drilled in the rim at the base of approximately 25 percent of the blades in order to evaluate the effectiveness of such holes in preventing crack growth.

The cracks did not grow through the holes during thermal-stress cycles to which the wheel was subjected by induction heating. A maximum rim temperature of 1150° F was reached. A few rather long cracks were present, which grew rapidly during the run, indicating that a considerable portion of the stress relief was occurring in the long cracks. The presence of these long cracks, which extended in the radial direction into the rim beyond the holes, made accurate evaluation of the effectiveness of the holes difficult. Measurements, which were made with electric crack gages, indicated that crack growth occurred during the cooling part of the thermal-stress cycle. This occurrence is in agreement with theoretical considerations, which indicate that high tensile stresses exist during the cooling part of the thermal-stress cycle as a result of the plastic flow in compression, which occurs during the heating part of the cycle.

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Carbon-Steel Disks

Two 13.5-inch-diameter SAE 1045 steel disks were subjected to thermal-stress cycles produced by induction heating. It was impossible to cause cracks to occur at notches in the rim as a result of thermal-stress cycles in which the rim was heated to 1350° F in 3 to 4 minutes. Plastic-flow figures were produced at the bottom of the notches. The hardness of the disks before the runs was Rockwell C-28 to C-30 and after the runs the hardness of the rim was Rockwell C-10. After a few cycles, the loss of hardness permitted plastic flow to occur.

Tool-Steel Disks

Five 13.5-inch-diameter tapered, molybdenum, high-speed tool-steel disks were subjected to thermal-stress cycles by induction heating. During the first part of the experiment, the disks were subjected to a maximum rim temperature of 800° F. The rim temperature was increased in 25° F increments, and 10 thermal-stress cycles were run at each increment. Semicircular notches in the rim were more effective than 60°-V notches in resisting cracking, which was to be expected. Holes of 1/8-inch diameter in the rim were found to be more effective in stopping crack growth than 1/16-inch-diameter holes. The disks, each of uniform hardness, covered the range of Rockwell C hardnesses from 11 to 65. The higher the hardness, the lower was the temperature gradient required to produce cracking; no reduction of hardness occurred as a result of experimenting. It was possible to obtain cracking in the rim of the tool-steel disk of Rockwell C-11, whereas no cracking was obtained in SAE 1045 disks, which had about the same rim hardness after investigating. At Rockwell C hardness of 11, the carbon-steel (SAE 1045) had a higher ductility than the tool steel and this difference was a factor of considerable importance in accounting for the cracking.

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TABLE I - DRILLED-HOLE LOCATIONS IN GAS-TURBINE WHEEL

Crack	Distance from base of blade (in.) (a)	Hole diameter (in.)	Crack	Distance from base of blade (in.) (a)	Hole diameter (in.)
195	1/4	1/16	99	1/4	1/16
1	1/4	1/16	100	1/4	1/16
2	1/4	1/16	113	3/16	1/8
3	1/4	1/16	114	3/16	1/8
16	3/16	1/8	115	3/16	1/8
17	3/16	1/8	116	3/16	1/8
18	3/16	1/8	129	3/16	1/16
19	3/16	1/8	130	3/16	1/16
31	3/16	1/16	131	3/16	1/16
32	3/16	1/16	132	3/16	1/16
33	3/16	1/16	146	1/4	1/8
34	3/16	1/16	147	1/4	1/8
48	1/4	1/8	148	1/4	1/8
49	1/4	1/8	149	1/4	1/8
50	1/4	1/8			
51	1/4	1/8	162	5/16	1/16
65	5/16	1/16	163	5/16	1/16
66	5/16	1/16	164	5/16	1/16
67	5/16	1/16	165	5/16	1/16
68	5/16	1/16	178	5/16	1/8
81	5/16	1/8	179	5/16	1/8
82	5/16	1/8	180	5/16	1/8
83	5/16	1/8	181	5/16	1/8
84	5/16	1/8			
97	1/4	1/16			
98	1/4	1/16			

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[a]Dimension B in figure 3.

TABLE II - PROPAGATION OF CRACKS NEAR HOLES IN GAS-TURBINE WHEEL

Number of thermal-stress cycles	Number of cracks				
	Not reaching holes	Stopping at holes	Propagated to holes during run	Extending beyond holes	Propagated beyond holes during run
0	16	27	--	5	--
5	11	29	5	8	3
15	9	31	2	8	0
20	9	31	0	8	0
30	9	30	0	9	1

TABLE III - GAS-TURBINE-WHEEL CRACK LENGTHS

(AVERAGE UPSTREAM AND DOWNSTREAM LENGTH)

Run	(a)	1	2	3	4
Number of cycles per run	0	5	10	5	10
Total number of cycles	0	5	15	20	30
Average length of cracks, (in.)	0.22	0.21	0.22	0.22	0.24
Total number of cracks measured	195	192	195	193	194
Average length of cracks shorter than 0.22 inch, (in.)	0.19	0.17	0.17	0.16	0.17
Number of cracks shorter than 0.22 inch	134	130	130	129	131
Average length of cracks longer than 0.50 inch, (in.)		0.57	0.64	0.71	1.02
Number of cracks longer than 0.50 inch	0	1	4	6	9

[a]Wheel as received.

Figure 1. - Turbine wheel at time it was removed from turbine-propeller engine.

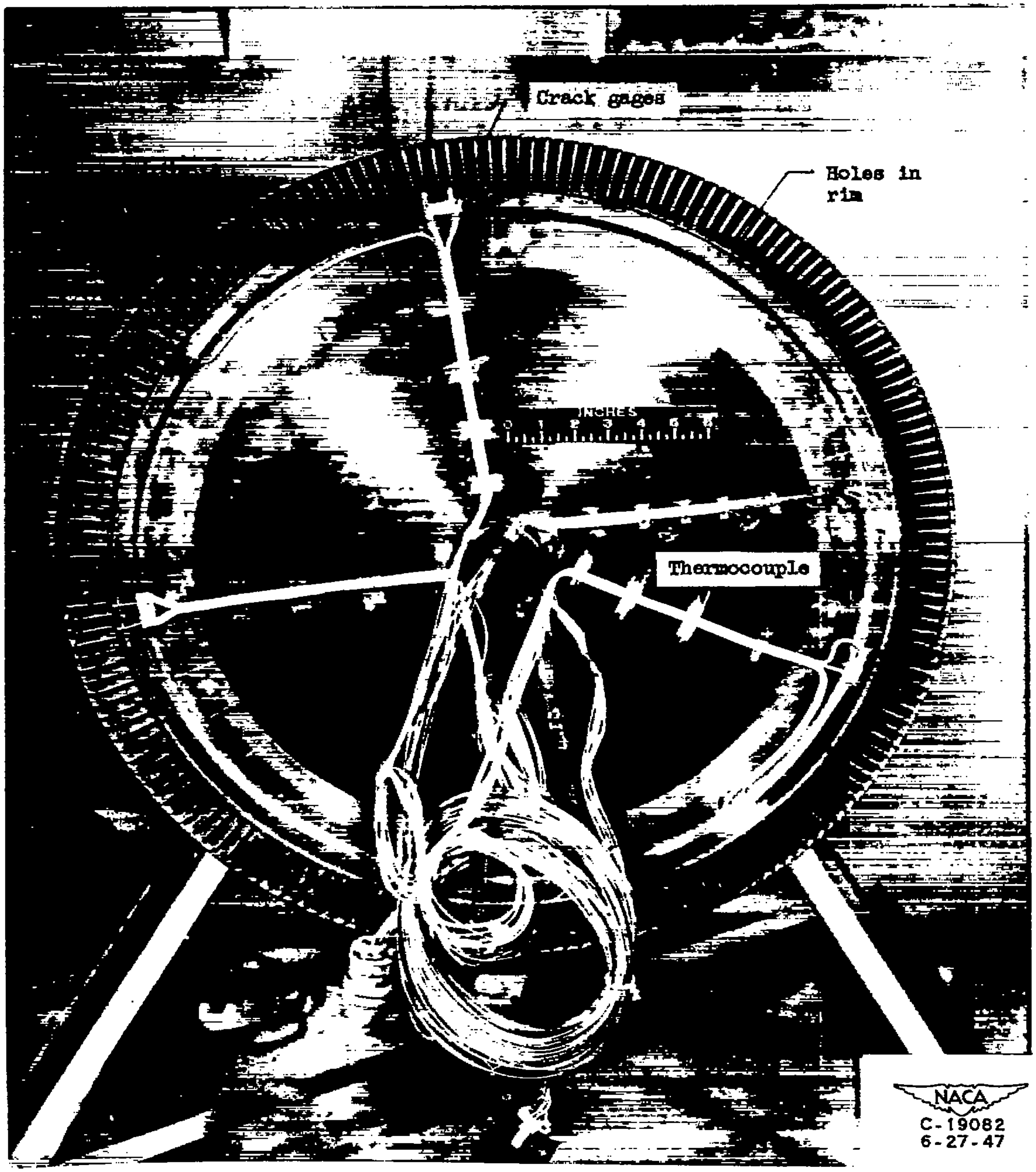

Figure 2. - Holes, thermocouples, and crack gages on downstream side of gas-turbine wheel.

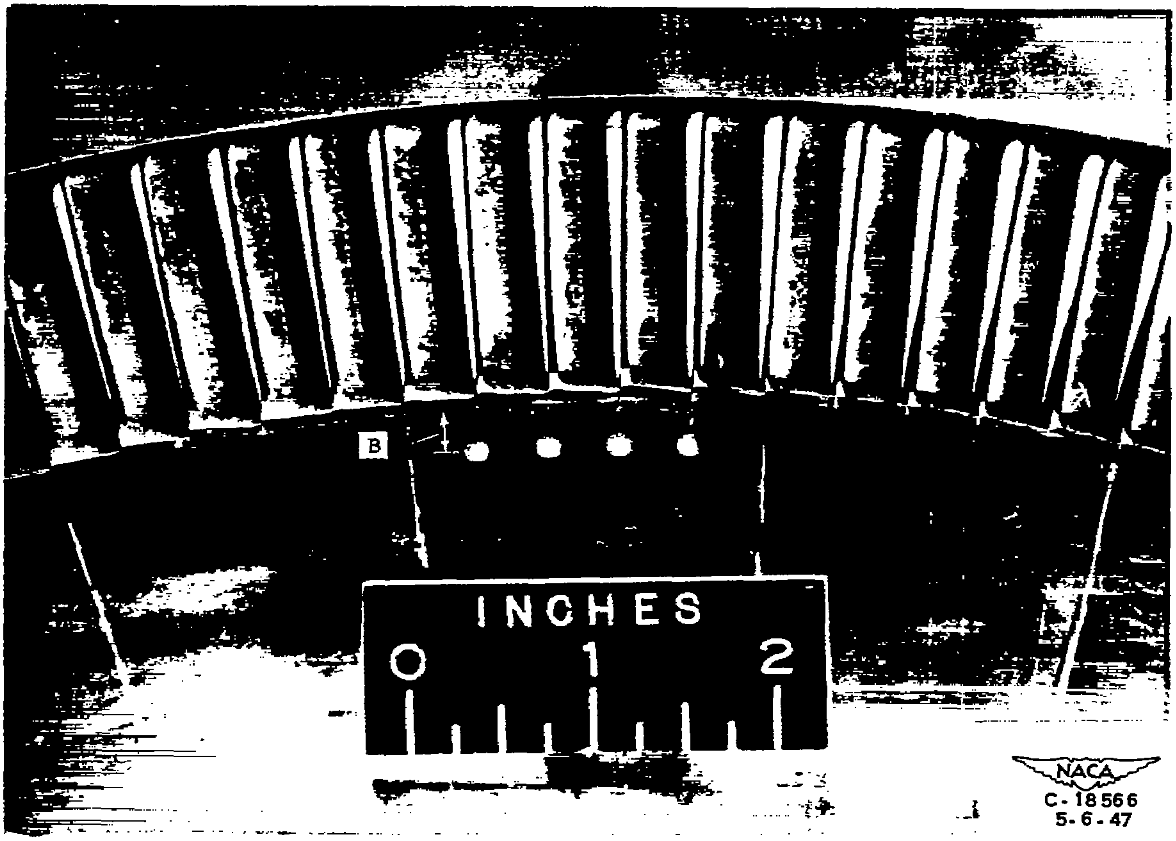

Figure 3. - Hole locations in gas-turbine wheel rim.

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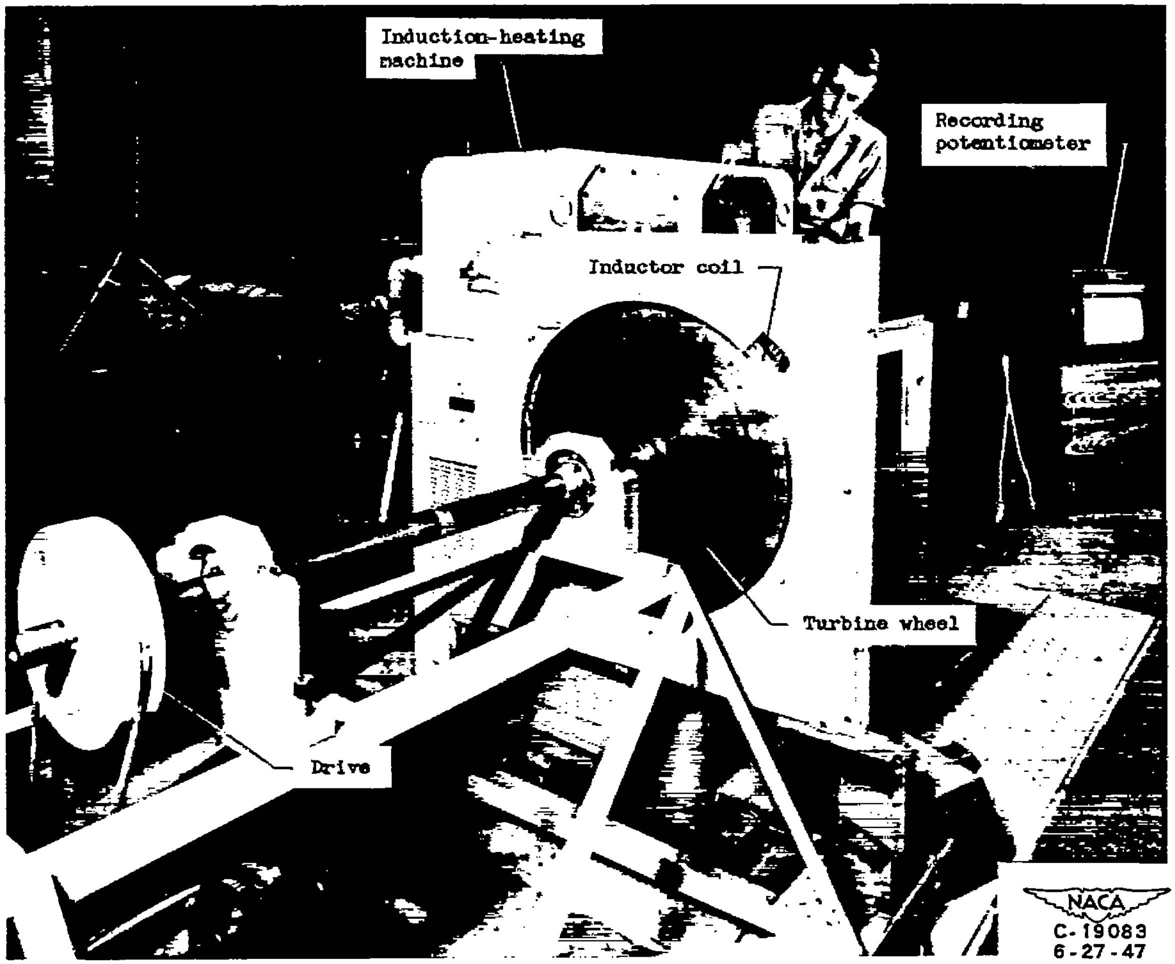

Figure 4. - Setup for investigation of turbine wheel.

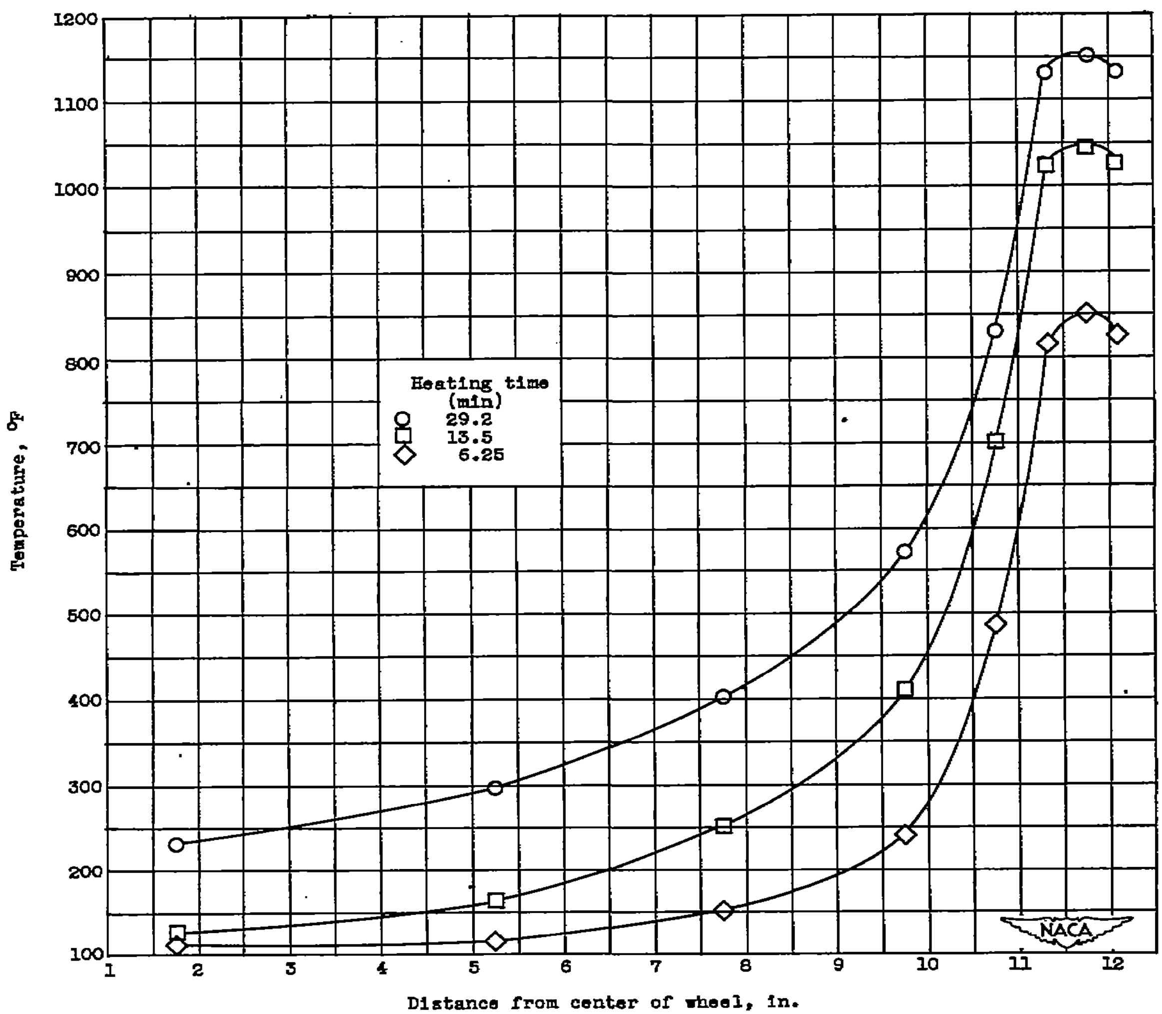

Figure 5. - Temperature distribution in gas-turbine wheel during heating.

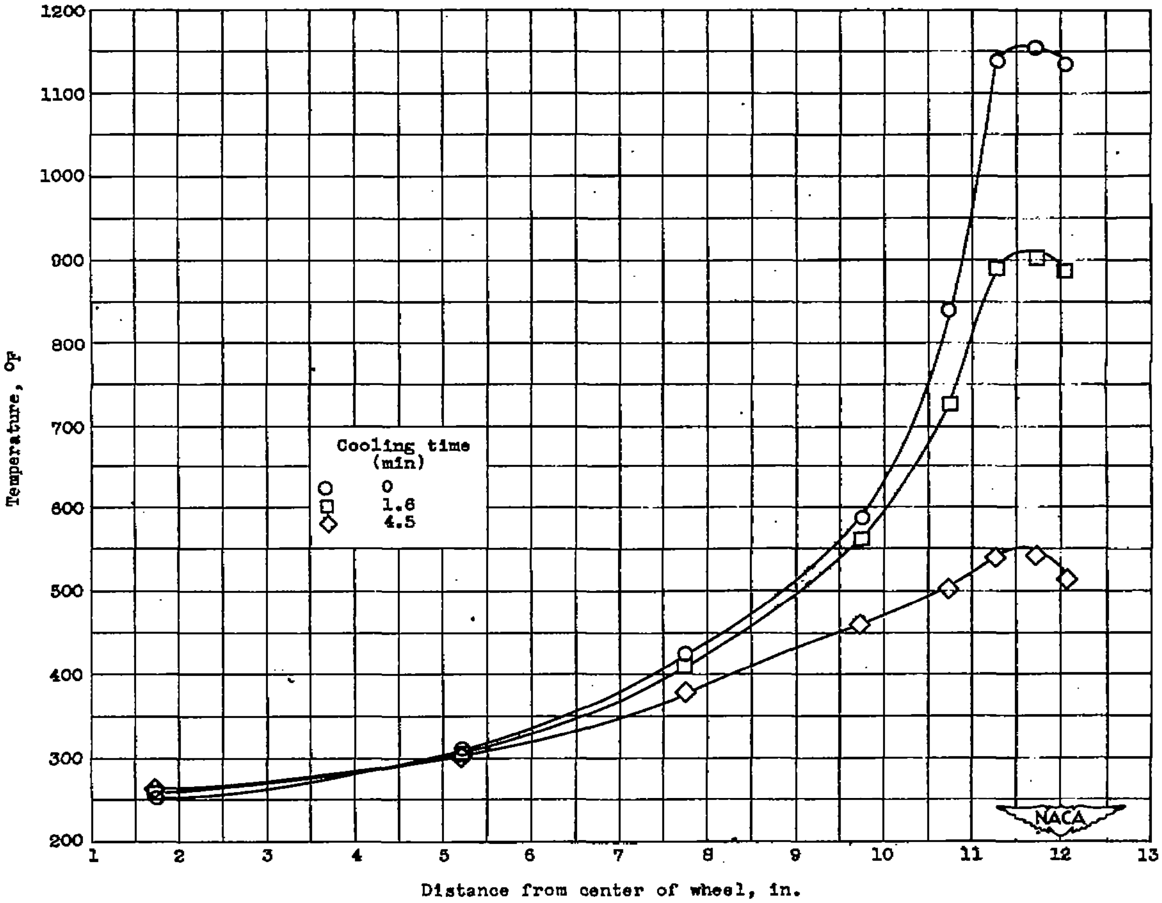

Figure 6. - Temperature distribution in gas-turbine wheel during cooling. Power on 31.5 minutes before cooling.

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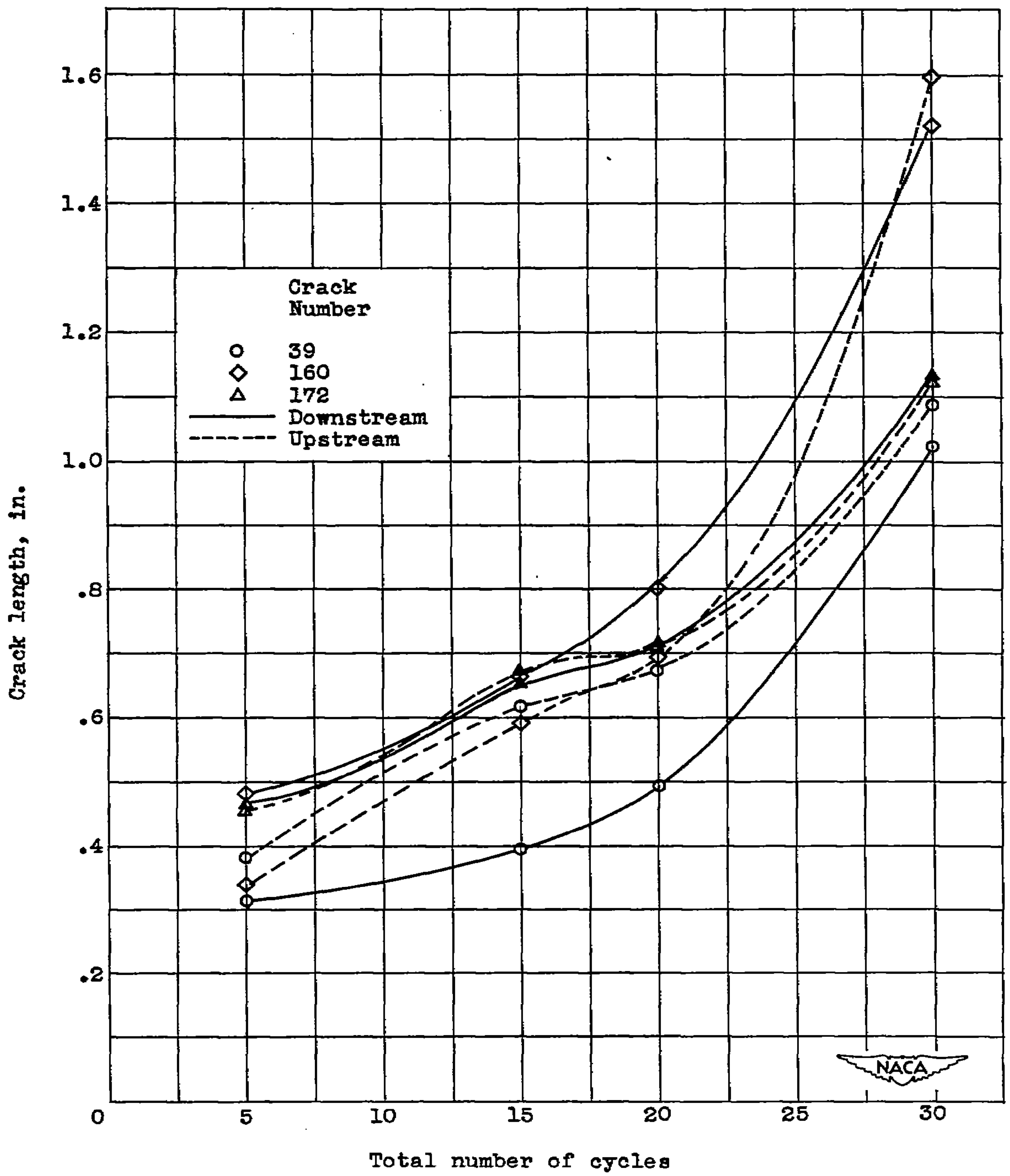
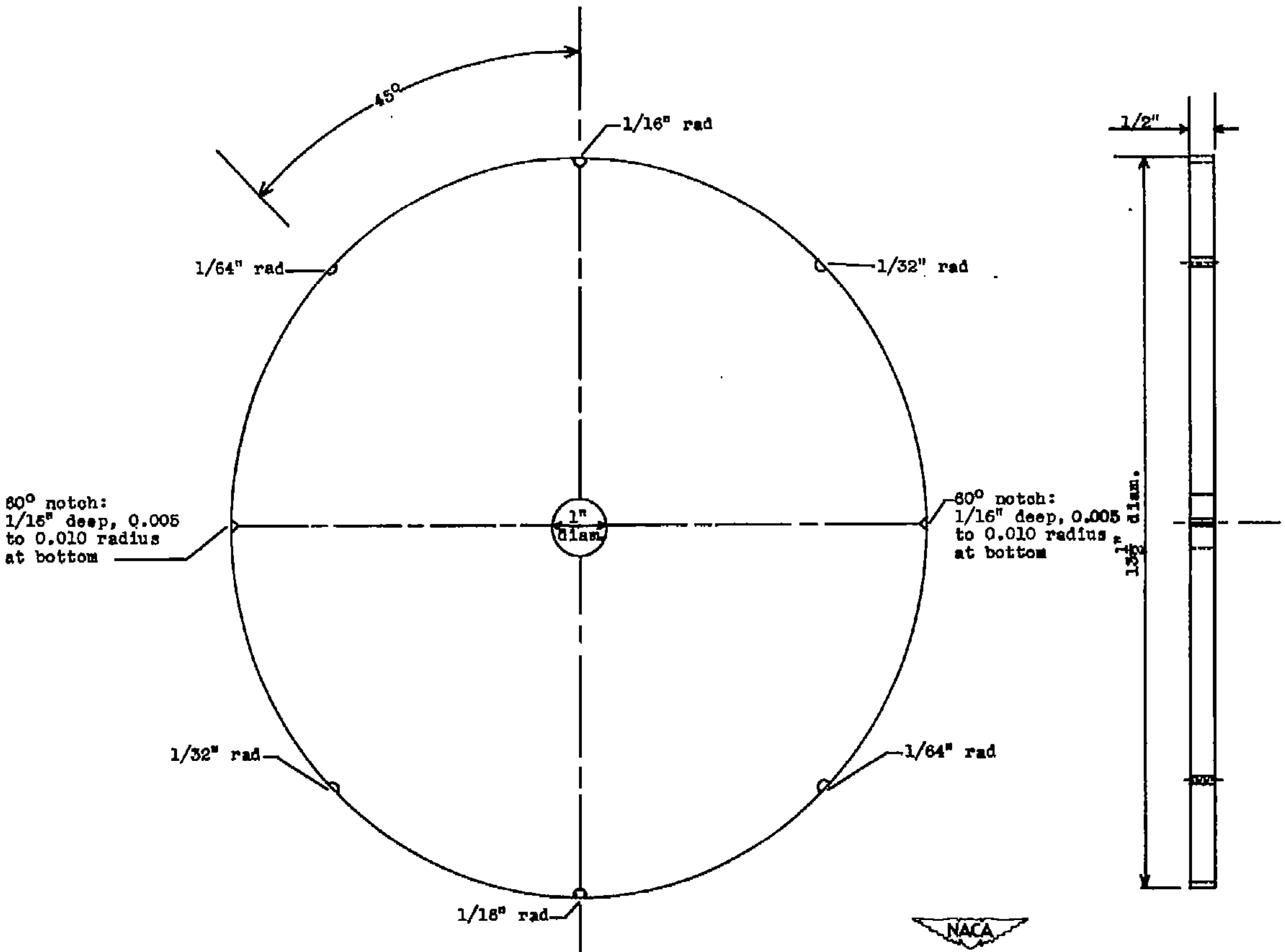
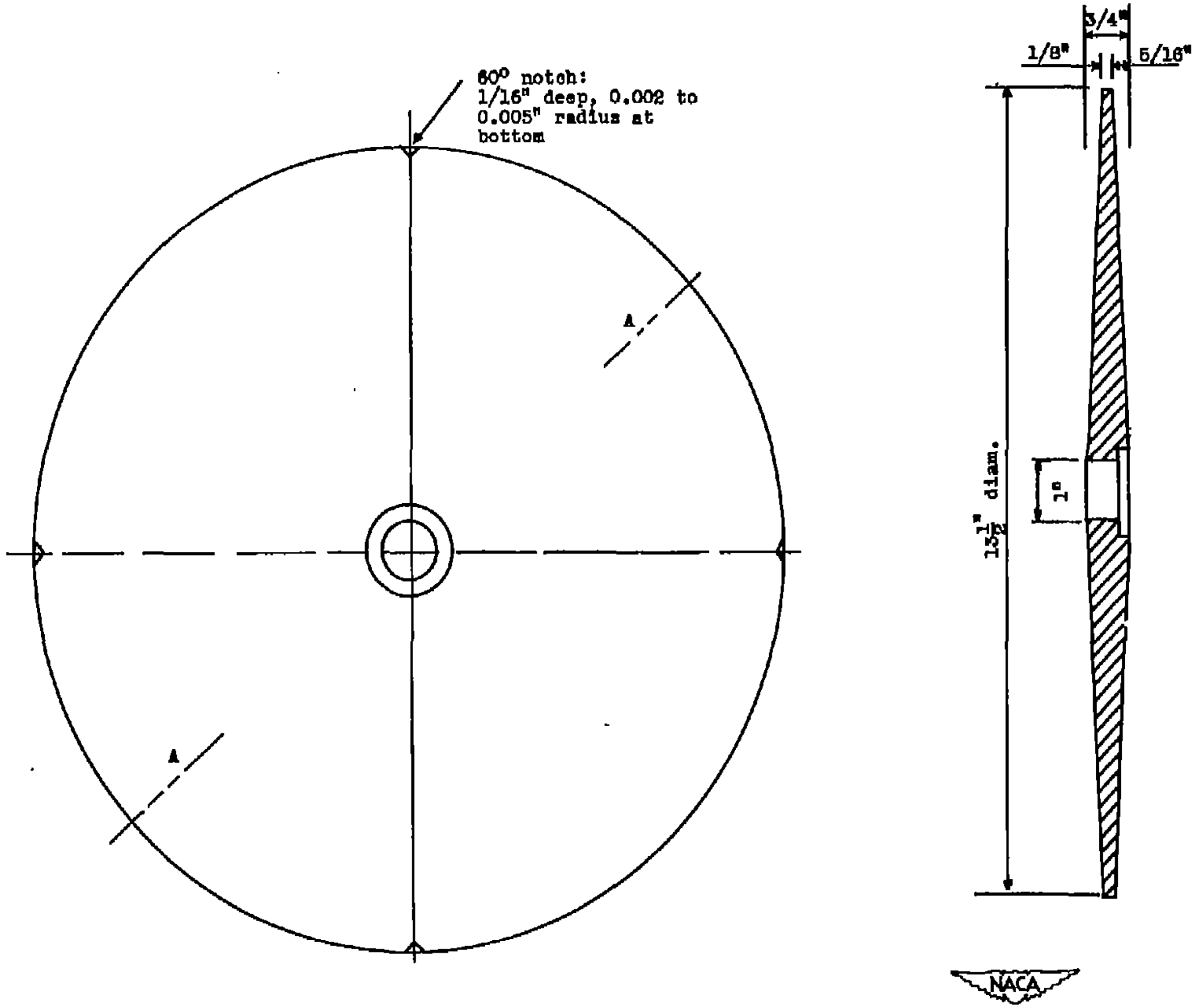


Figure 7. - Growth of long cracks in gas-turbine wheel.



(a) Flat disk.

Figure 8. - Notched-rim 13.5-inch-diameter disk.



(b) Tapered disk.

Figure 8. - Concluded. Notched-rim 13.5-inch-diameter disk.

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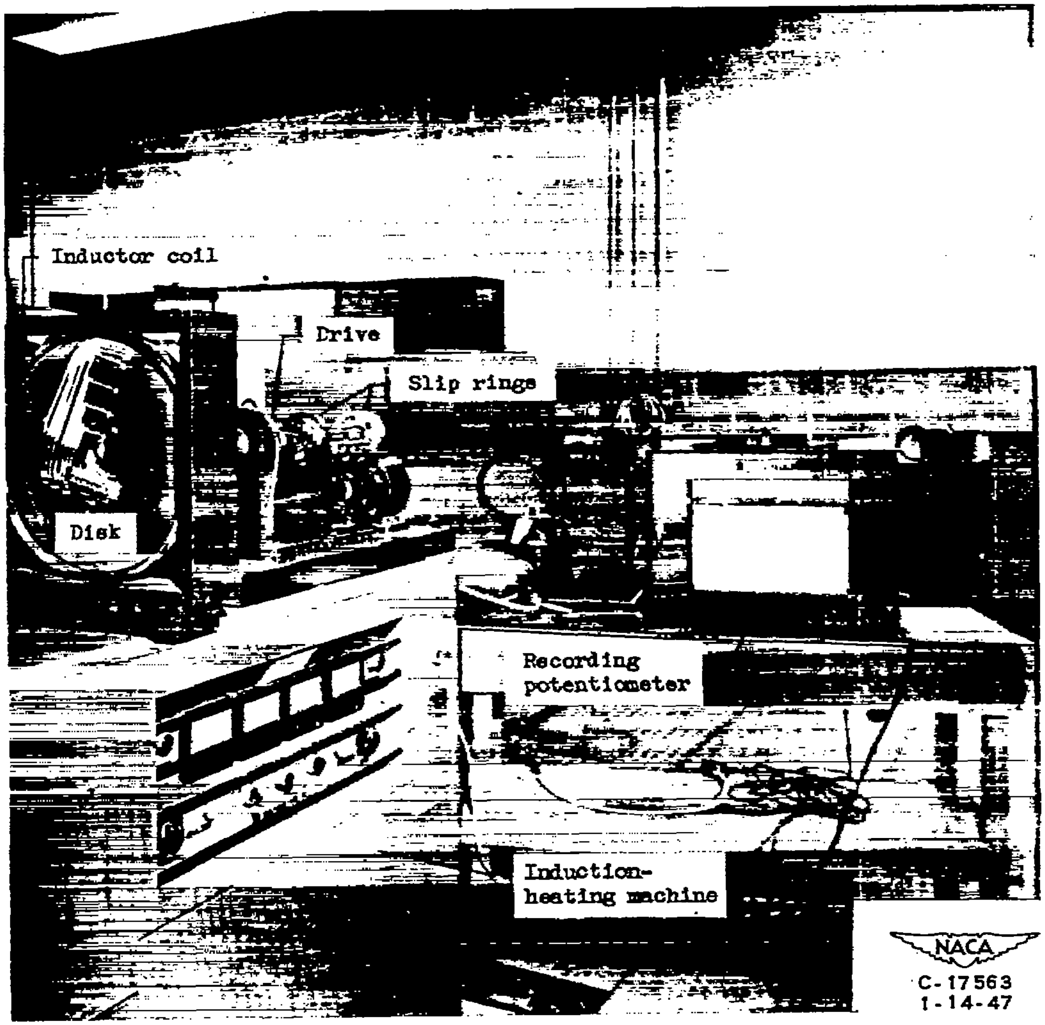

Figure 9. - Setup for investigation of 13.5-inch-diameter disks.

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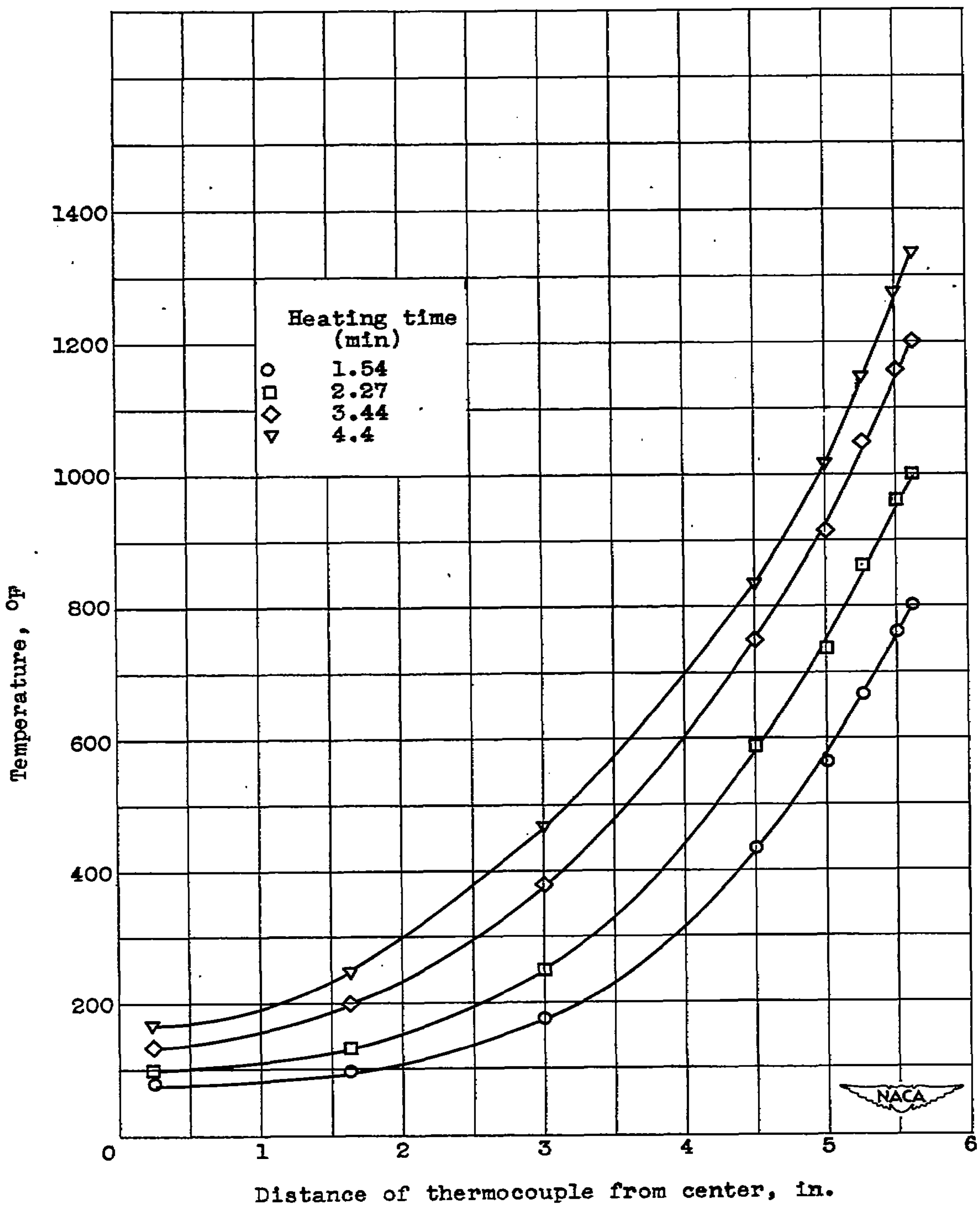

Figure 10. - Temperature distribution in 13.5-inch-diameter disks during heating.

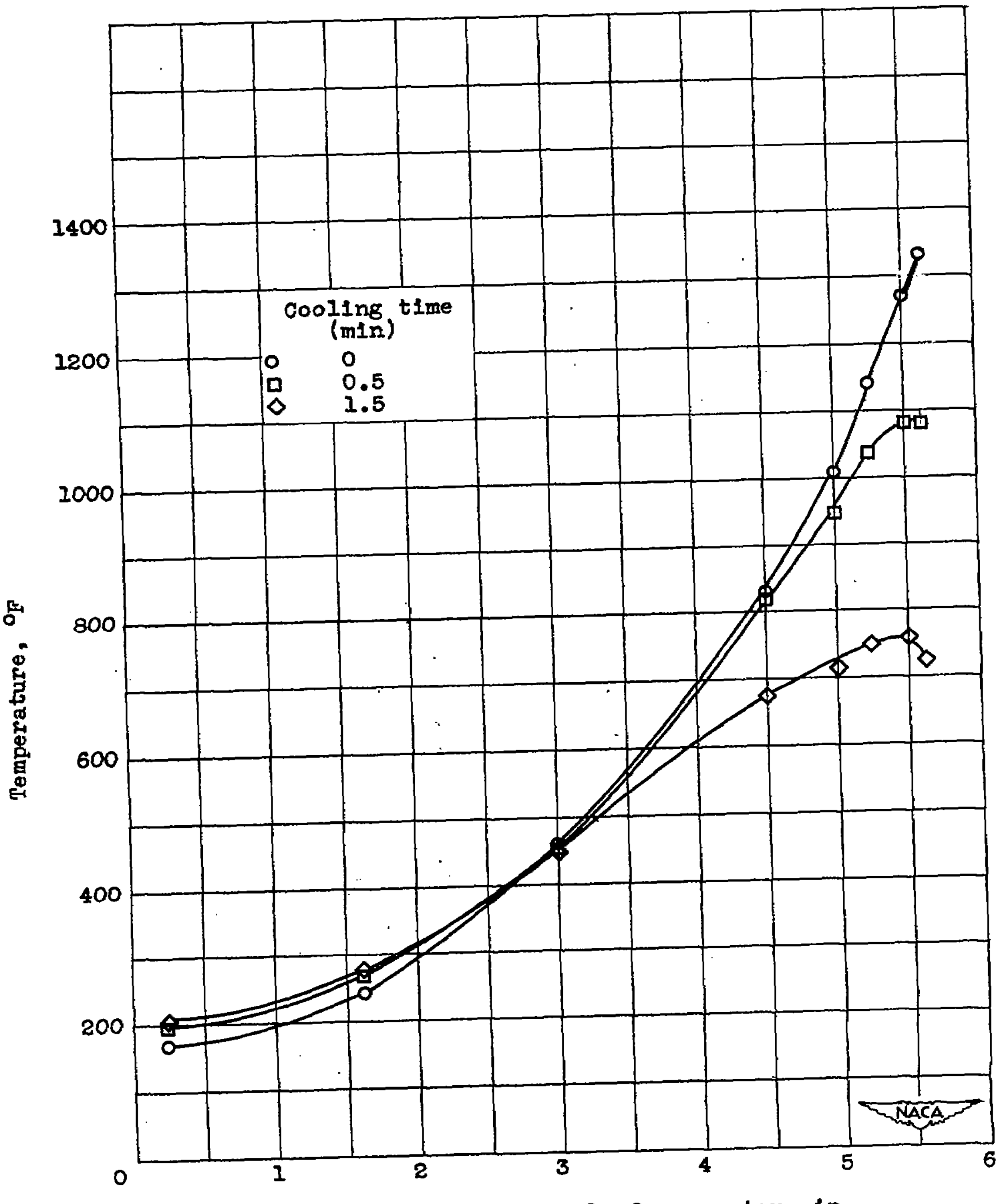

Figure 11. - Temperature distribution in 13.5-inch-diameter disks during cooling. Power on 4.4 minutes before cooling.

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Figure 12. - Condition of SAE 1045 13.5-inch-diameter disk after runs.

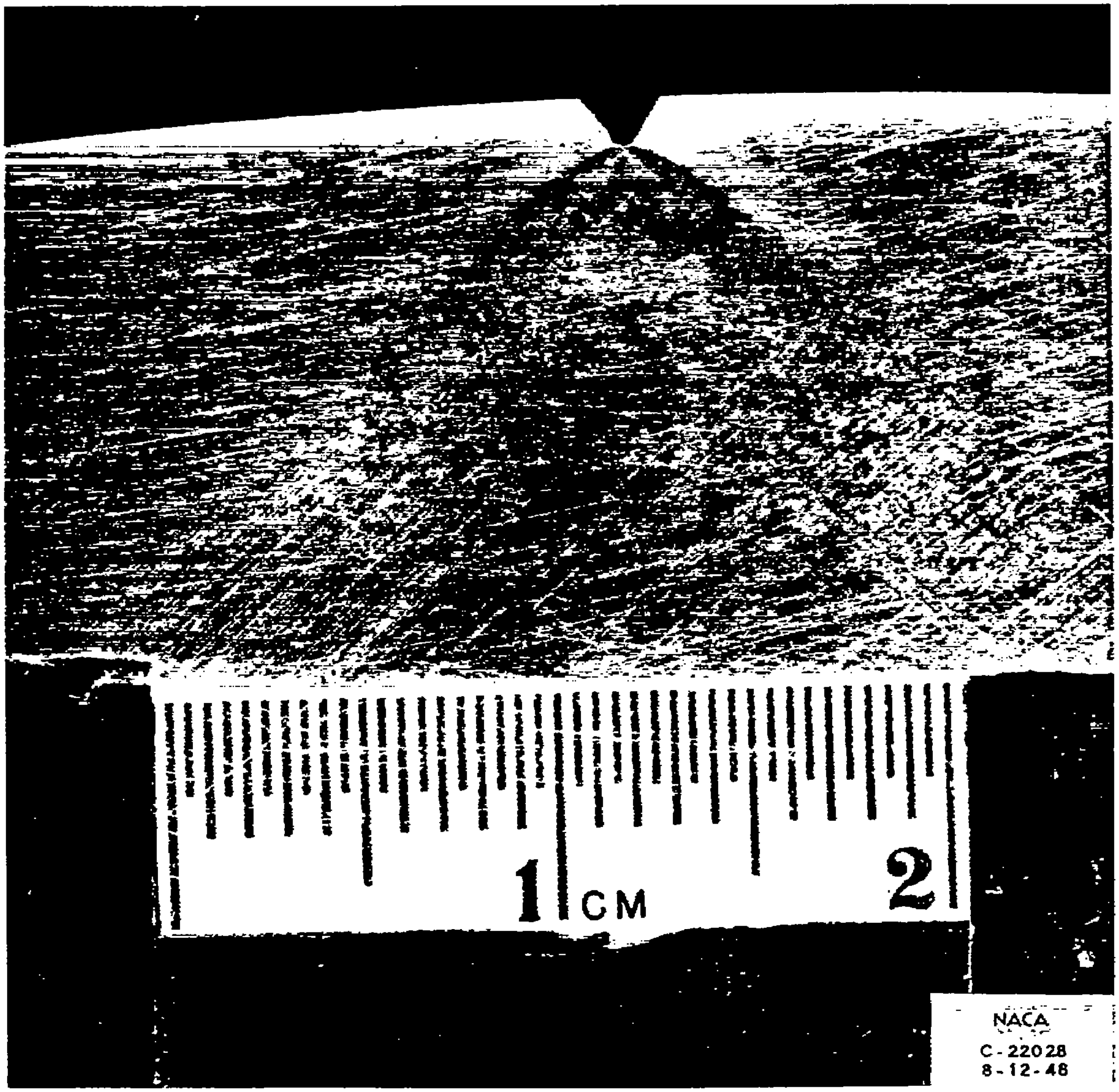

Figure 13. - Plastic flow at notch in SAE 1045 13.5-inch-diameter disk.

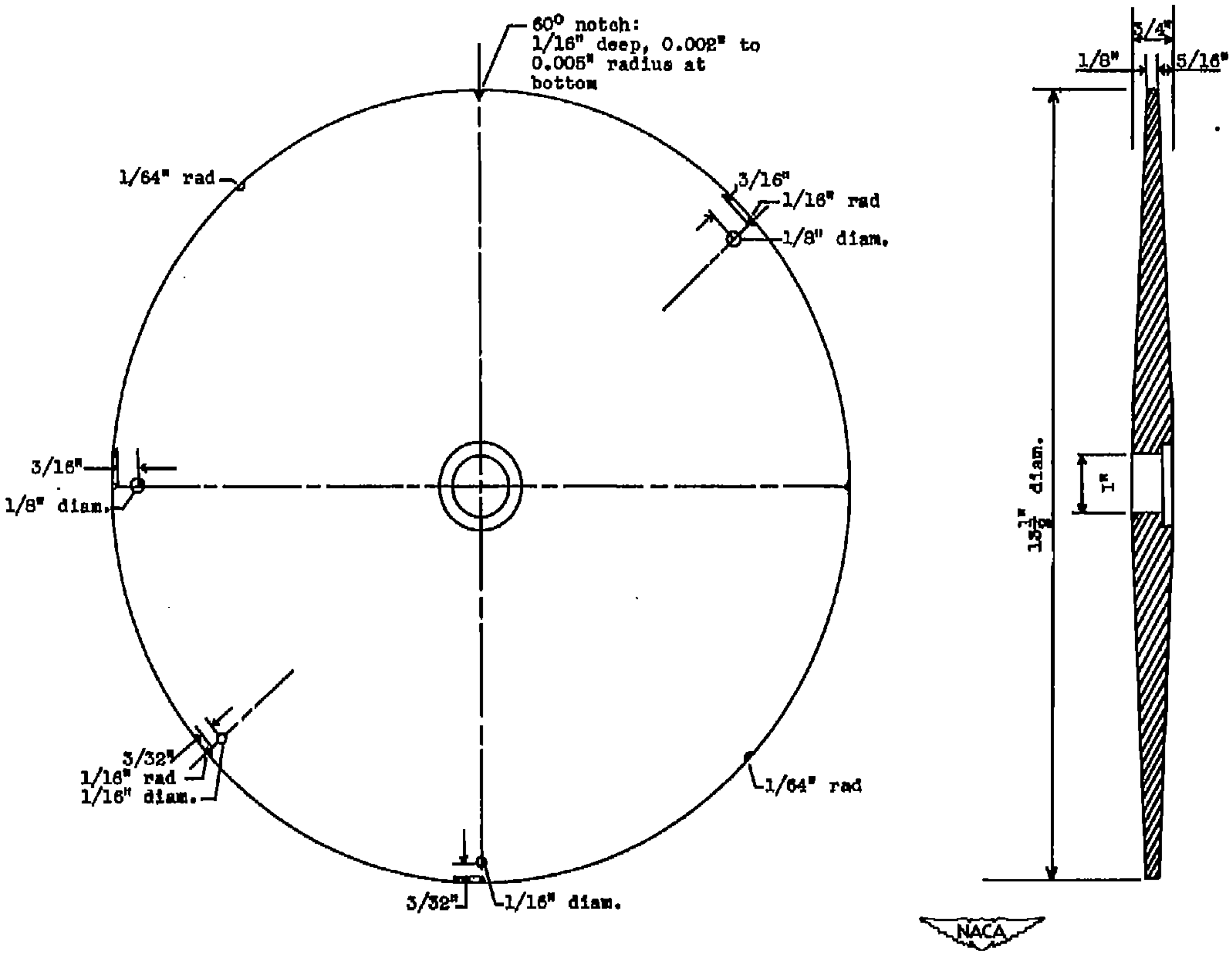

Figure 14. - Notched- and drilled-rim 13.5-inch-diameter tapered tool-steel disk.

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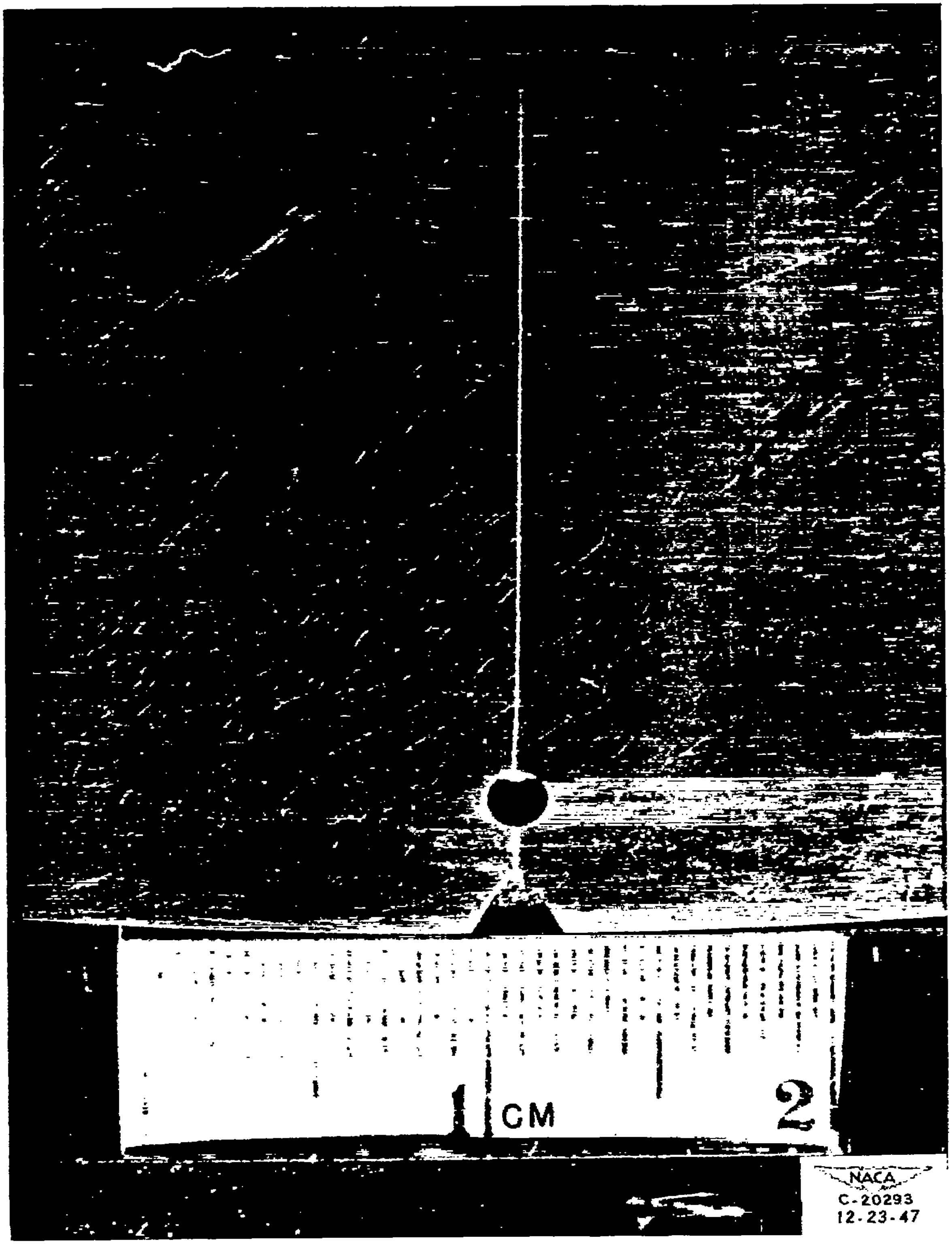

Figure 15. - Radial crack in 13.5-inch-diameter tool-steel disk. Hardness, Rockwell C-60.

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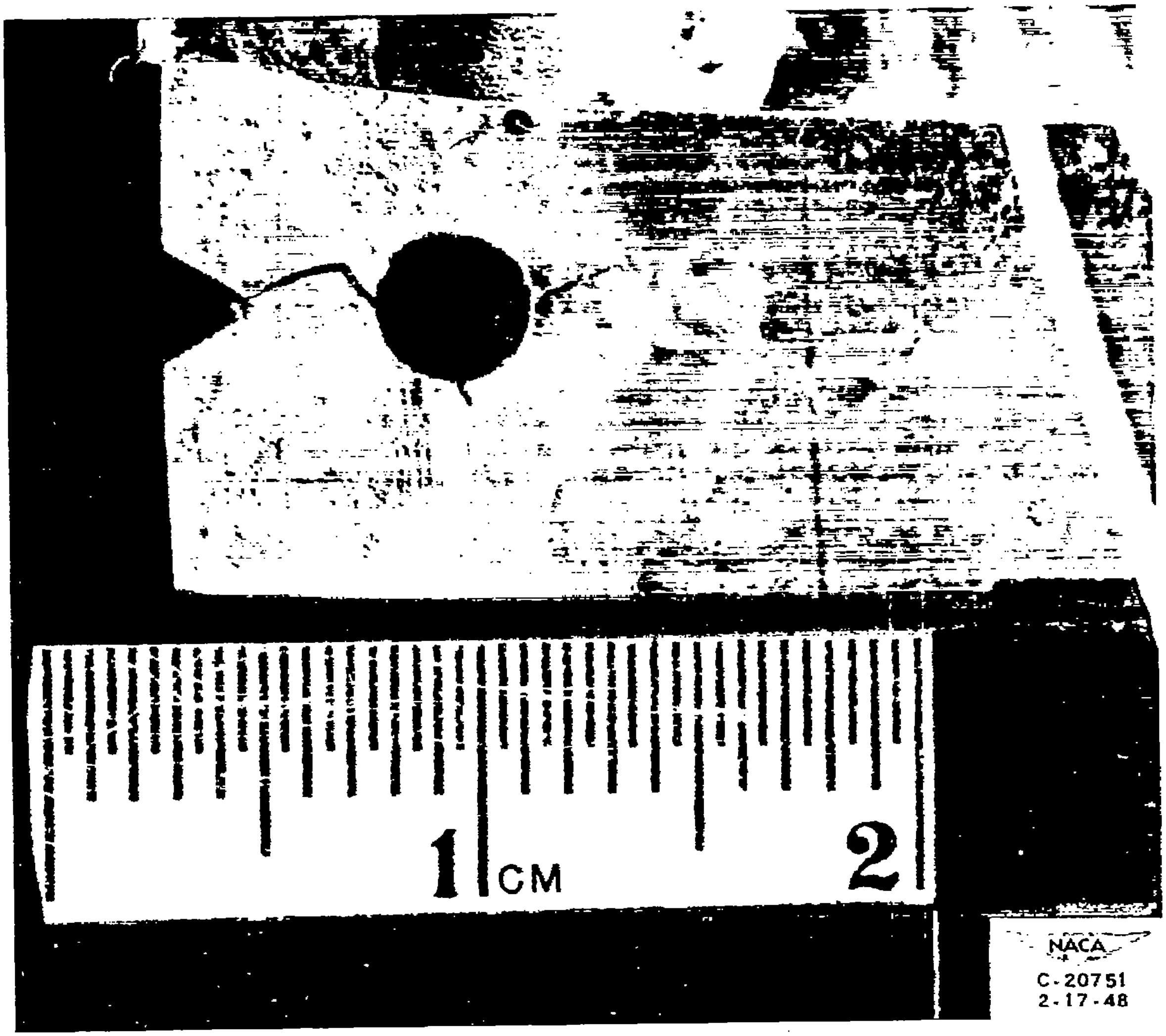

Figure 16. - Crack in 13.5-inch-diameter tool-steel disk. Hardness, Rockwell C-11.

1148

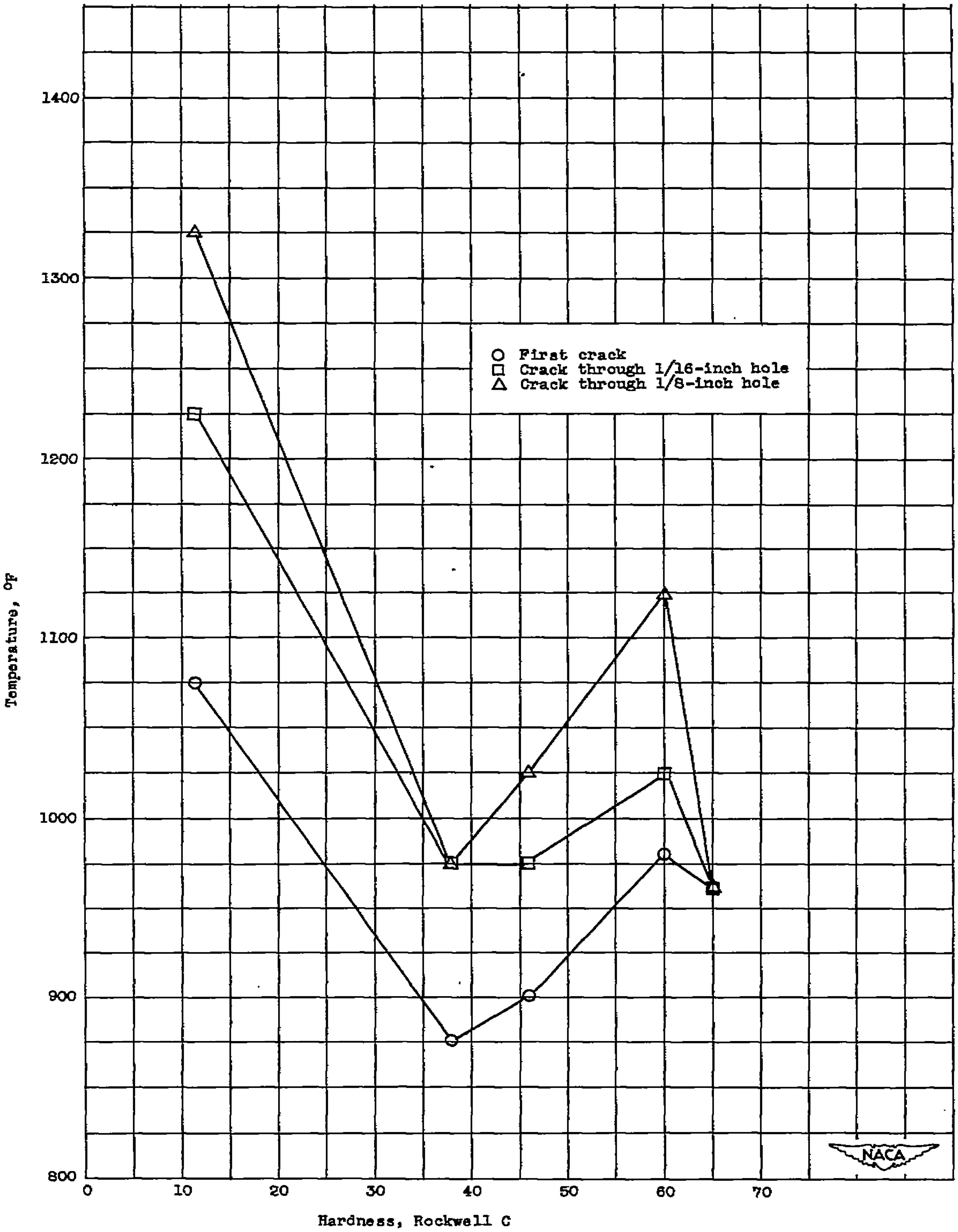

Figure 17. - Cracking temperatures in 13.5-inch-diameter tool-steel disks.